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June 27, 1997

Dr. Joseph Kravitz, Program Officer
Office of Naval Research - Code 322GG
Department of the Navy
Ballston Centre Tower One
800 N. Quincy St.
Arlington, VA 22217-5660

Re: PERFORMANCE/FINAL TECHNICAL REPORT for -
MCS Transects of the Gorda Rise and Costa Rica Rift:
Two ONR-Funded Surveys aboard *R/V Ewing*
Grant No. NOOO14-94-1-0110

Dear Joe:

We enclose our Performance/Final Technical Report for the above-mentioned grant. Copies have also been sent to the individuals listed below, as outlined in the Grant Schedule.

If you require any further information, please do not hesitate to contact John Diebold at 914-365-8524, or via email: johnd@ldeo.columbia.edu.

We thank the Office of Naval Research for this award.

Very truly yours,

John B. Diebold
Research Scientist

Carolyn Z. Mutter
Associate Research Scientist

enclosures

cc: Ms. Angela Potter, Resident Rep., Boston, MA
Director - Naval Research Lab, Washington, DC
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Performance Final/Technical Report

NOOO14-94-1-0110

MCS Transects of the Gorda Rise and Costa Rica Rift: Two ONR-Funded Surveys aboard *R/V Ewing*

John B. Diebold and Carolyn Z. Mutter

Introduction

The consensus reached at the ONR Workshop on Investigations of Young Oceanic Crust, held at Friday Harbor, Washington in March of 1993, was that marine geophysical surveys should be conducted in one or more "corridors" in the Eastern Pacific. It was recognized that multichannel seismic [MCS] reflection profiling was an important part of such surveys, despite their relatively high cost. Excellent results were gained during two such profiling efforts, which were carried out as "add-on" surveys, attached in one case to a larger, NSF-funded survey, and in the other, carried out during a transit leg. In both cases, transit, mobilization and demobilization costs were minimal, and the maximum amount of data possible was obtained, given the available funding.

Gorda Rise

The Gorda Rise segment is unusual in that spreading rates have, for the past 10 my, been highly asymmetric, offering a chance to examine conjugate sections of crust created at the same time and place, but with crustal accretion rates that differ by a factor of two. The Gorda Rise transect was shot during *R/V Ewing*'s (EW-9413) transit from Prince Rupert, BC, to Coos Bay, Oregon in September, 1994. Four days of ship time was budgeted for the transect. A half day was required for deploying and recovering the MCS equipment, which consisted of a 4 km digital 160 channel hydrophone array, and a 10-gun 3005 cu. in. source array. During the 3.5 days available for data acquisition, about 15,200 shots were fired, along a transect from 17 my crust on the Pacific plate, across zero age crust at the ridge crest, and eastward to 6 my crust on the Gorda plate (Fig. 1). These data were gathered into 61,400 CDPs. Images of the Layer 2A/2B interface were obtained by the constant-velocity normal moveout [CVNMO] method (Vera and Diebold, 1994). In most places, the imaging was successful over a wide range of stacking velocities, and

the apparent thickness of the layer varied according to the velocity used. In order to determine the true velocity and thickness of Layer 2A, a great number of CDP gathers were examined and analyzed by ray tracing. The explanation for the poor stacking velocity discrimination was that in many cases, the postcritical arrivals forming the image were seen in only a few traces (Fig. 2). Another surprise is the frequent appearance (visible in Fig. 2) of arrivals from Layer 2B. A compilation of the ray tracing results (Fig. 3) shows several interesting features. Thickness of Layer 2A does not seem to vary systematically with age, though there appears to be an increase in velocity from 2.5 km/sec to 3 km/sec, which takes place within the first 1-2 my. Greater non-age-dependent variations are seen in a few places.

5-6 my crust on the Gorda plate features 2A thicknesses which become vanishingly small. In the conjugate area on the Pacific plate, increases in 2A thickness and velocity are seen. As shown by Fig. 4, our interpretation of the thinning of 2A east of the ridge crest is well supported by the data. In CDP gathers from the conjugate Pacific area (Fig. 5), there remains the possibility that layer 2A is thin and undetected, and that we are modeling the 2B arrivals instead. In any case, we can certainly say that Layer 2A thicknesses are a bit greater in this intermediate spreading rate segment than they are at the fast-spreading East Pacific Rise, and that greater variations in thickness and velocity are present.

Costa Rica Rift

The study of upper crustal seismic characteristics at the poorly known Costa Rica Rift axis was initiated with a Hydrosweep survey conducted along N-S corridors spaced at approximately 8 km range over the shallower western 70 km of the approximately 140 km spreading segment. The survey revealed the major features of the rift and the fabric of northern flank of the rift out to about .5 my and the southern flank of the rift out to about 1 my (Fig. 6). The spreading center is characterized by a series of en echelon rift valleys that step to the north from west to east. The axial asymmetry observed for the western region of the Costa Rica Rift is not unlike that observed at the adjacent Ecuador Rift (Carbotte and Macdonald, 1993); both rift systems show a shoaling of the axial rift valley at toward the western limit of each segment and lineated topography reminiscent of that observed on the slower spreading Mid Atlantic Ridge.

With raw hydrosweep data in hand, it was possible to design an axial seismic investigation utilizing a 3005 cu in airgun source array, a 4 km 160 channel digital streamer configured in 25 m

groups, and dispensable sonobuoys, to investigate the most robust-looking part of the spreading segment, and the crust formed along a flow line south from this segment toward the 504B area. The airgun array was fired at a 13 second shot interval (randomized at ± 250 msec) at a ship speed of approximately 4.5 kts (over the ground), giving an optimal shot spacing of 30 m for the 10 s seismic records sampled at 2 msec. This shot spacing was chosen so that subsequent processing to reduce the influence of rough, diffractive topography could be accomplished with minimal spatial aliasing. Multichannel seismic (MCS) and sonobuoy profiles were acquired in isochron orientations along flanks and rift of a valley of about 3000 m depth centered at about 3°20'N, 83°50'W (Fig. 6). Three MCS profiles were also acquired across the axis of this feature. These object of these profiles was to capture the axial and near axis character of the uppermost crust (Layer 2A) so that the evolution of the features resolved in this crust could be studied along a flow line extending to the south. Additional MCS and sonobuoy profiles were acquired along isochron line intersections of the flow line in crust of .75 my (Fig. 6), 2.2 my (Fig. 7a), and 5.5 my age (Fig. 7b) to ensure the best possible resolution of intra-crustal features. In three days, 600 km of very high quality MCS data and several good sonobuoy profiles were acquired.

Layer 2A has already been well resolved in detailed seismic studies of the faster spreading East Pacific Rise; Layer 2A consists of crust having a characteristic low velocity (2 - 3 km/s) and a rapid velocity increase to about 5.0 km/s at the base (e.g., Vera and Diebold, 1993). It is likely formed of extrusive igneous rocks at the surface overlying intercalated intrusive and extrusive rocks grading to an entirely intruded dike complex at the base of the layer. Studies to date indicate that seismic Layer 2A forms a 100 - 150 m thick layer at the ridge axis, thickens to 400 - 700 m within a km or so of the axis, and then appears to remain relatively constant in thickness to ranges of 10 km or so from the axis with subsequent evolution unknown. The Costa Rica Rift study and Gorda Rise study are the first to attempt resolution of Layer 2A beyond a few million years age. Iterative analysis of Layer 2A from constant velocity CDP stacks of 300 km of isochron lines positioned in crust of 0 (Line 1268; Fig. 8a), 0.75 (Line 1276; Fig. 8b), 2.2 (Line 1280; Fig. 8c), and 5.5 my (Line 1284; Fig. 8d) from the Costa Rica Rift yields the following results:

• Layer 2A is formed entirely at the axis of spreading, and forms a considerably thicker unit at the intermediate spreading (33 mm/yr) Costa Rica Rift (450-600 m) than at the faster spreading East Pacific rise axis.

• The thickness of Layer 2A remains approximately constant (450 - 600 m) out to at least 2.2 my.

• The interval velocity of Layer 2A increases from about 2800 - 3000 m/s at the spreading axis to 3300 - 3500 m/s at the adjacent rift high and flanks, and remains approximately constant out to at least 2.2 my.

• The interval velocity of Layer 2A in 5.5 my old crust is significantly higher (4500 - 4700 m/s) and the layer considerably thinner (200 - 300 m) than that formed prior to 2.2 my. This layer thickness is comparable to the seismic Layer 2A thickness observed at 5.9 my old crust of Hole 504B (125 - 200m).

In addition:

• An axial magma chamber (AMC) event has been clearly imaged at 2600 - 2800 m depth beneath the 3000 m deep axis of the CRR, providing perhaps the first unequivocal observation of an AMC in a rift valley setting (Fig. 9). Both AMC depth and Layer 2A thickness are considerably greater than observed along the faster spreading EPR.

• Crust formed .75 my ago appears to be about 1 km thicker (1.9 s twtt) than crust formed 5.5 my ago (1.5 s twtt).

Using Layer 2A thickness as a proxy for extrusive layer thickness, these results provide the first compelling evidence that crust formed from a deeper AMC forms a thicker extrusive layer than crust formed by shallower AMCs, and have led to the first model formulation for extrusive thickness based on depth to the AMC (Buck, et al., submitted). This model integrates the combined influences of AMC overburden, density structure, melt viscosity, and flexural effects to show how thicker extrusives are predicted from deeper AMCs (Figure 10). Extrusion is self-regulated through the integrated pressures on the axial magma lens itself. This magma pressure is determined by the depth of the lens, the average density of the rocks over the lens, and the flexural load supported by the lithosphere above the lens.

Conclusions

The cooperation of Lamont-Doherty's Marine Department, and investigators at Woods Hole Oceanographic Institution, i.e., R. Detrick and J. Collins, enabled us to collect large aperture MCS data in two areas, without the usual added costs of transit and mobilization. The cost benefit to the Navy was, therefore maximized, and the results have justified the effort expended. According to the problems that were addressed, and due to the cooperative environments, two kinds of surveys were planned and carried out. The Gorda Rise data, acquired during a transit leg, were shot in the

form of a single, continuous transect, which imaged Layer 2A from fully mature (17 my) crust, to the ridge axis and beyond, covering areas with variable spreading rates. The Costa Rica Rift data were acquired cooperatively during another survey, and a grid of lines were recorded. In both cases, the survey goals were met and exceeded.

Publications resulting from this work:

Buck, W.R., S.M. Carbotte and C.Z. Mutter, Controls on Extrusion at Mid-Ocean Ridges, submitted, *Geology*.

Mutter, C.Z., Seismic and Hydrosweep Study of the Western Costa Rica Rift, *EOS Trans.AGU,* **76**, 595, 1995.

Figure Captions

Figure 1. Track map of MCS portion of Lamont MCS cruise EW-9413, superimposed on crustal ages contoured in millions of years.

Figure 2. Four successive CDP gathers are superimposed, showing the characteristic layer 2A arrival at 5.05 sec, reduced traveltime and at offsets between 2.9 and 3.4 km.

Figure 3. Compiled results of ray-trace analysis of CDP gathers. 2A velocity climbs quickly from 2.6 km/sec to 3.3 km/sec, with several large (apparently structure-related) variations. 2A thickness is quite variable.

Figure 4. In one area (5 my, E. side of ridge) 2A is very thin, as clearly shown by the refraction which crosses the basement reflection at 3 km (4.5 sec, reduced traveltime).

Figure 5. On the other side of the ridge, Layer 2A is thick and fast.

Figure 6. Binned and interpolated hydrosweep data from the Costa Rica Rift area, with multichannel seismic (MCS) track indicated by solid line. MCS track was positioned according to raw hydrosweep data and is well aligned with the seafloor fabric. Line 1268 is located on zero age crust of the Costa Rica Rift (profile shown in Figure 8a) in a shallow rift valley. Line 1276 is located along an isochron of 0.75 my old crust (profile shown in Figure 8b).

Figure 7. Binned and interpolated hydrosweep data from 2.2 my old (Line 1280, above) and 5.5 my old (Line 1284, below) crust of the Costa Rica Rift. Hydrosweep and MCS profiling was done simultaneously; note that orientation is not quite as well positioned with respect to seafloor structure as in the near axis setting (Figure 6).

Figure 8. Isochron profiles from the Costa Rica Rift. Stacks mute near offset data to minimize distortion of the event from the base of seismic Layer 2A, designated 2A in profiles. (a) Line 1268, zero age crust. Layer 2A is evident at about 0.4 ± .05 s twtt beneath the seafloor (~600m, interval velocity of 2900 m/s), with an axial magma chamber (AMC) event evident at about 1.25 s twtt beneath the seafloor (~2700 m). The AMC is somewhat weak in this section owing to the severe inside mute; a full, migrated stack of the AMC is also shown in Figure 9. (b) Line 1276, 0.75 my old crust. Layer 2A is evident at about 0.35 ± .025 s twtt beneath the seafloor (~600m, interval velocity of 3400 m/s). A MOHO event is visible at the base of the crust at about 2.0 s twtt beneath the seafloor. (c) Line 1280, 2.2 my old crust. Layer 2a remains at about 0.35 ± .025 s twtt (~600m, interval velocity of 3400 m/s) beneath the seafloor. (d) Line 1284, 5.5 my old crust. Layer 2a is located at about .22 ± .015 s twtt (~500 m, interval velocity of 4600 m/s) beneath the top of igneous basement (note there is a significant sediment accumulation of about .35 s twtt above this). MOHO is evident at 1.5 s twtt beneath the top of igneous basement and thus the crust is significantly thinner in this setting than observed 3.3 my previously (Line 1280).

Figure 9. Stacked and migrated time sections from the intermediate-fast spreading EPR at 17°N (left) and the intermediate spreading CRR (right). The base of Layer 2A and the AMC occur at significantly greater depths at the CRR axis than at the EPR.

Figure 10. Model predictions from Buck et al. (submitted) for four sets of parameters (overburden, overburden + viscous, overburden + flexure, overburden + viscous + flexure) compared with observations of seismic Layer 2A thickness at the ridge axis as a function of depth to the axial magma chamber. Schematics depict overburden mechanisms for regulating the equilibrium thickness of the extrusive layer Ze at a mid-ocean ridge with a magma lens at a depth Zl. For a deeper magma lens the extrusive layer has to be thicker to give the same average density of the

rocks overlying the magma lens. For reflection data, averages and standard deviations (where available) measured from detailed surveys within these areas are given. Two-way traveltimes to the Layer 2A and AMC events are converted to depth using velocities derived from on-axis refraction data in the same area unless otherwise specified. Data for 17°S EPR are repicked from the along-axis profile of Mutter et al., 1995; 9°N EPR, 2A thickness is from Harding et al., 1993 and AMC depth from Kent et al., 1993; 16°N and 17°N EPR are from Carbotte et al., 1996. Depth conversion is carried out using velocities from on-axis ESP solution of Vera et al., 1990 for EPR at 9°N; Juan de Fuca, AMC depth is from reflection data presented in Morton et al., 1987 and Layer 2A thickness is estimated from two-dimensional seismic refraction study of Macdonald et al., 1994. For this data point the range of axial 2A thickness and AMC depths observed are shown. We note that the evidence for an axial melt lens at this site is debatable since the crustal reflection identified by Morton et al., 1987 is weak and reflection polarity cannot be determined. Costa Rica Rift, from Mutter, 1995. Refraction results are from expanding spread profiles shot along the ridge axis: 14°S EPR, from Mutter et al., 1995; 17°S EPR, Detrick et al., 1993; 13°N EPR, Harding et al., 1989; 9°N EPR, Vera et al., 1990.

Gorda Ridge Transect EW9413

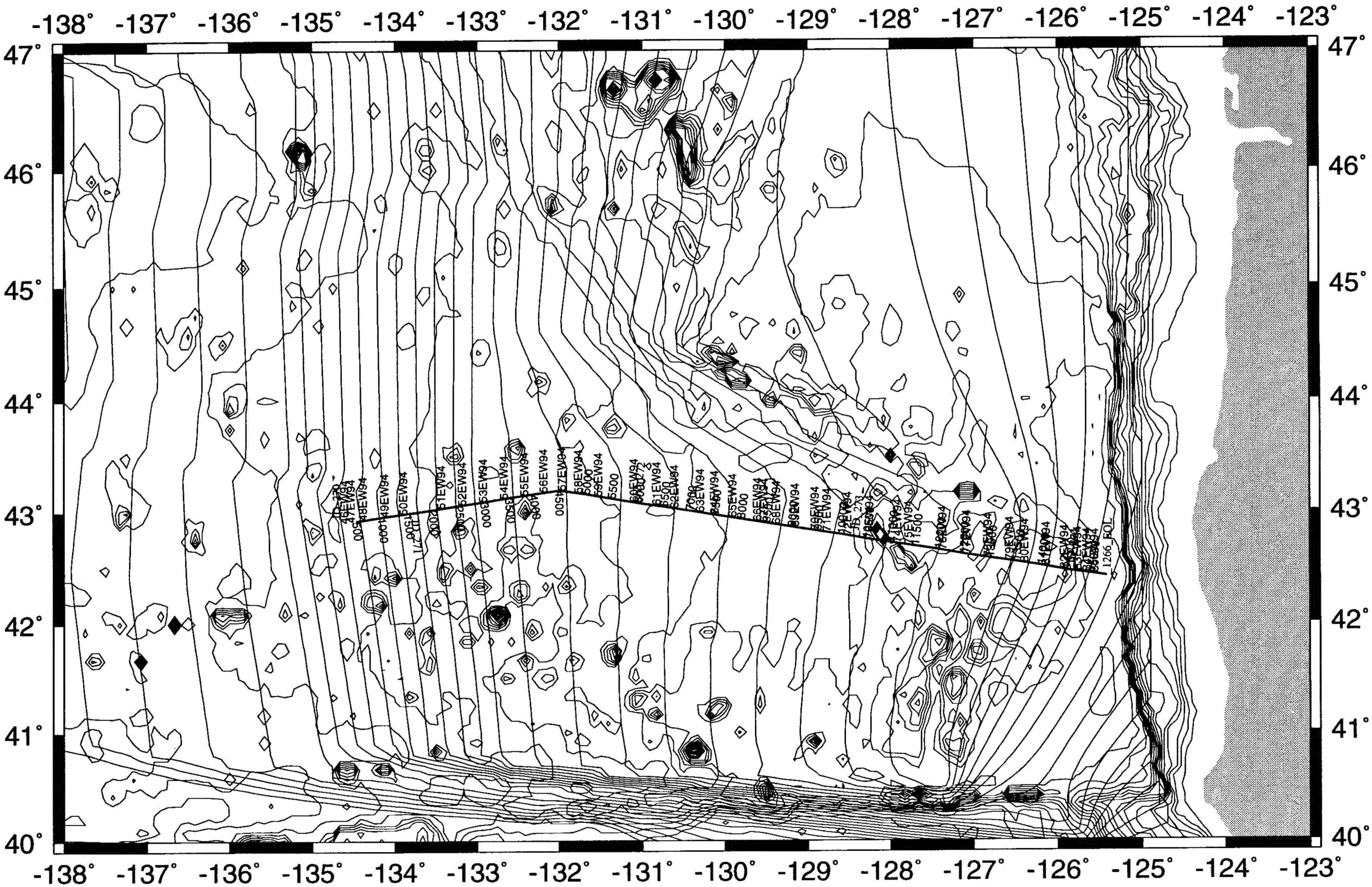
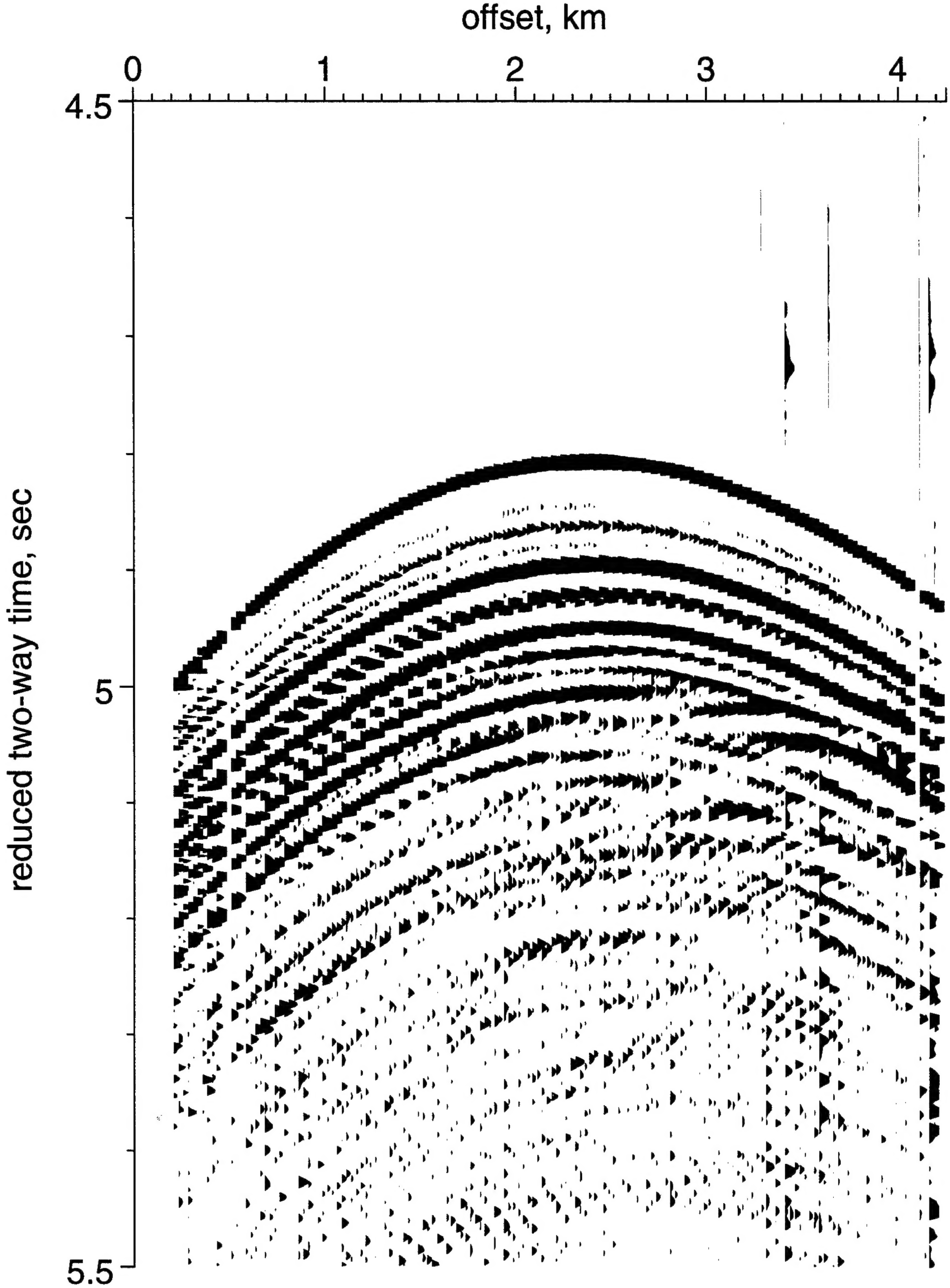


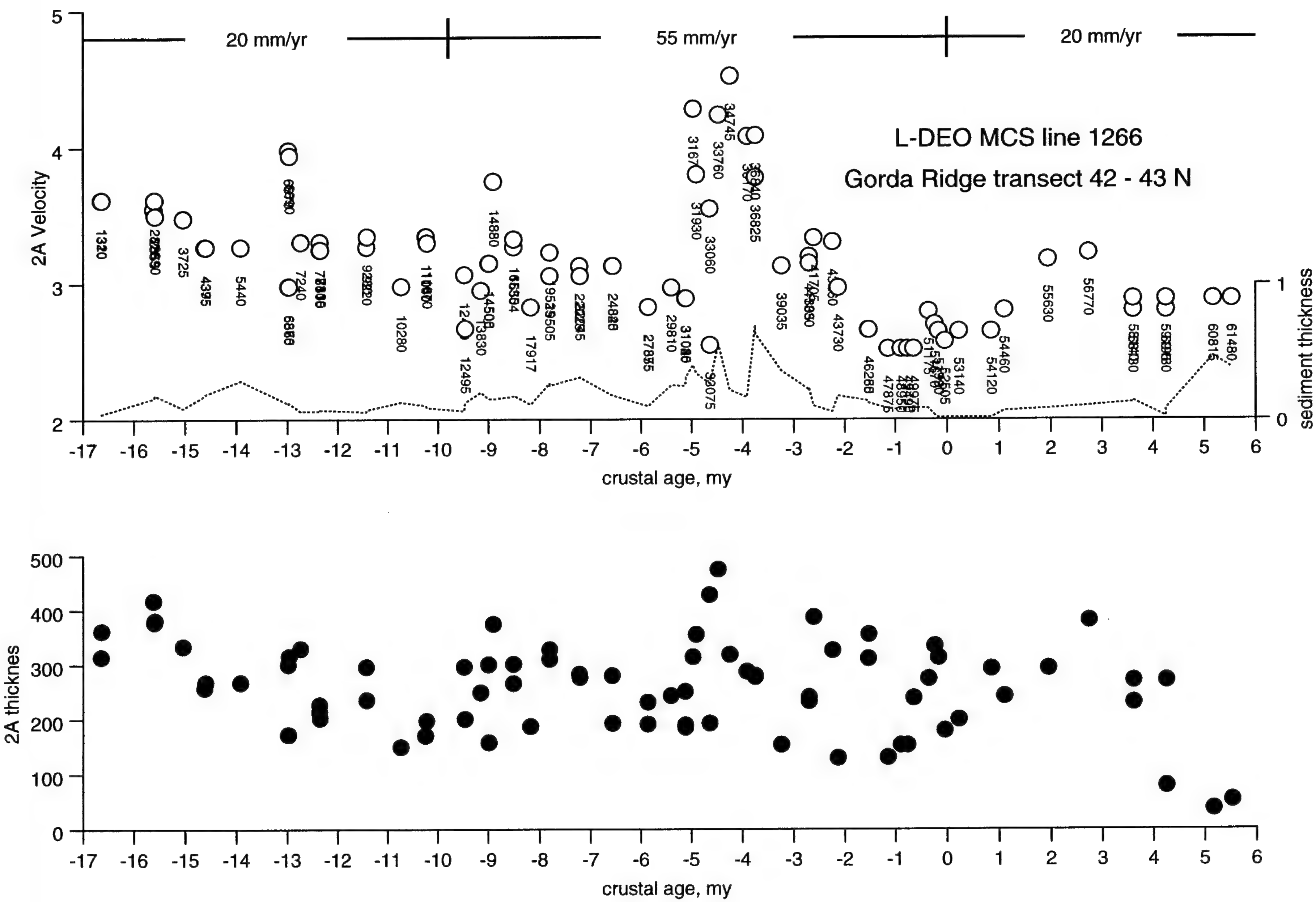
Figure 1



Crustal age -11 my. Layer 2A base refraction appears on only a few traces

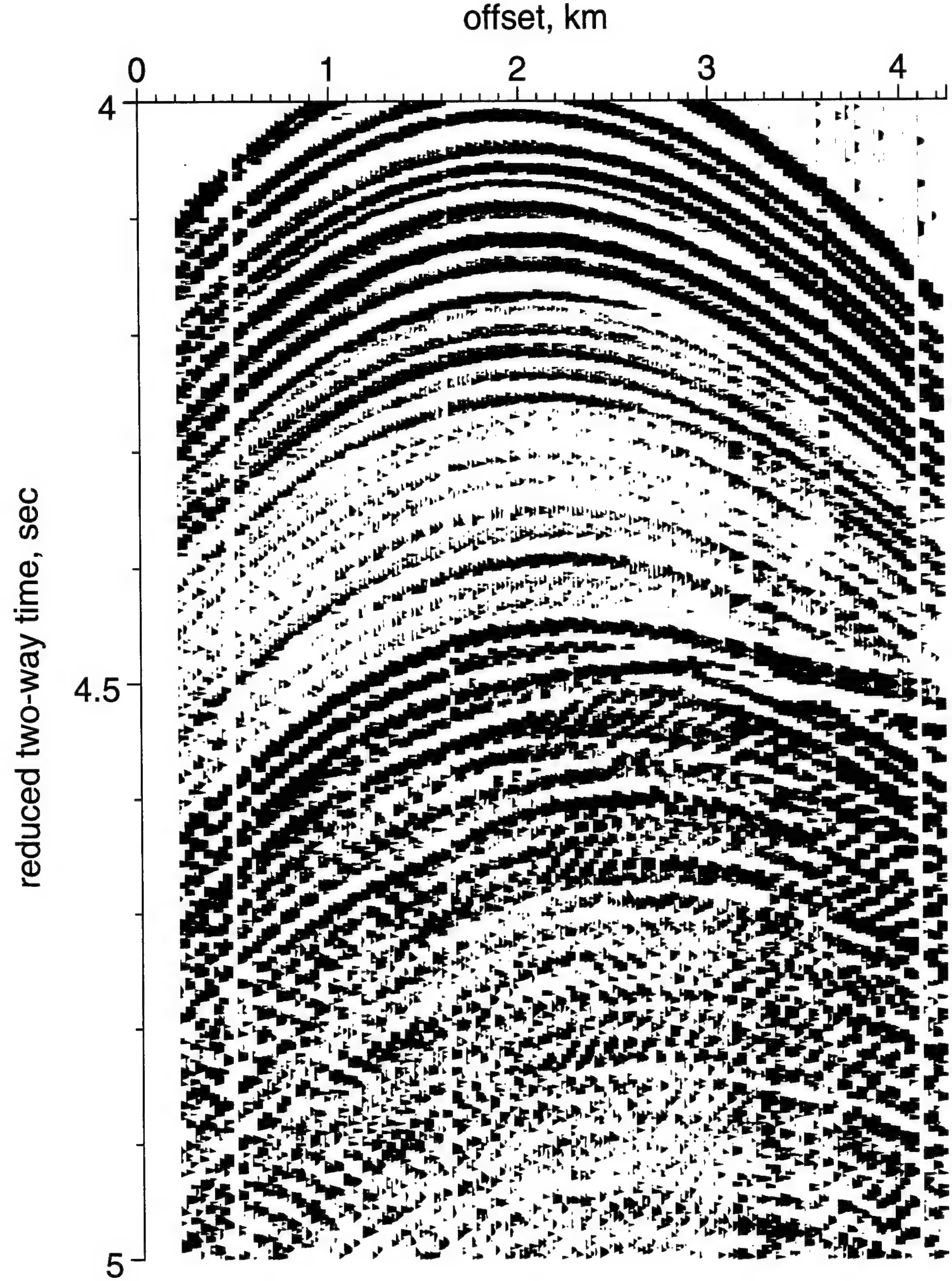
L-DEO MCS line 1266 cdp 10280

Figure 2



L-DEO MCS line 1266
Gorda Ridge transect 42 - 43 N
20 mm/yr
55 mm/yr
20 mm/yr
2A Velocity
sediment thickness
crustal age, my
2A thicknes
crustal age, my

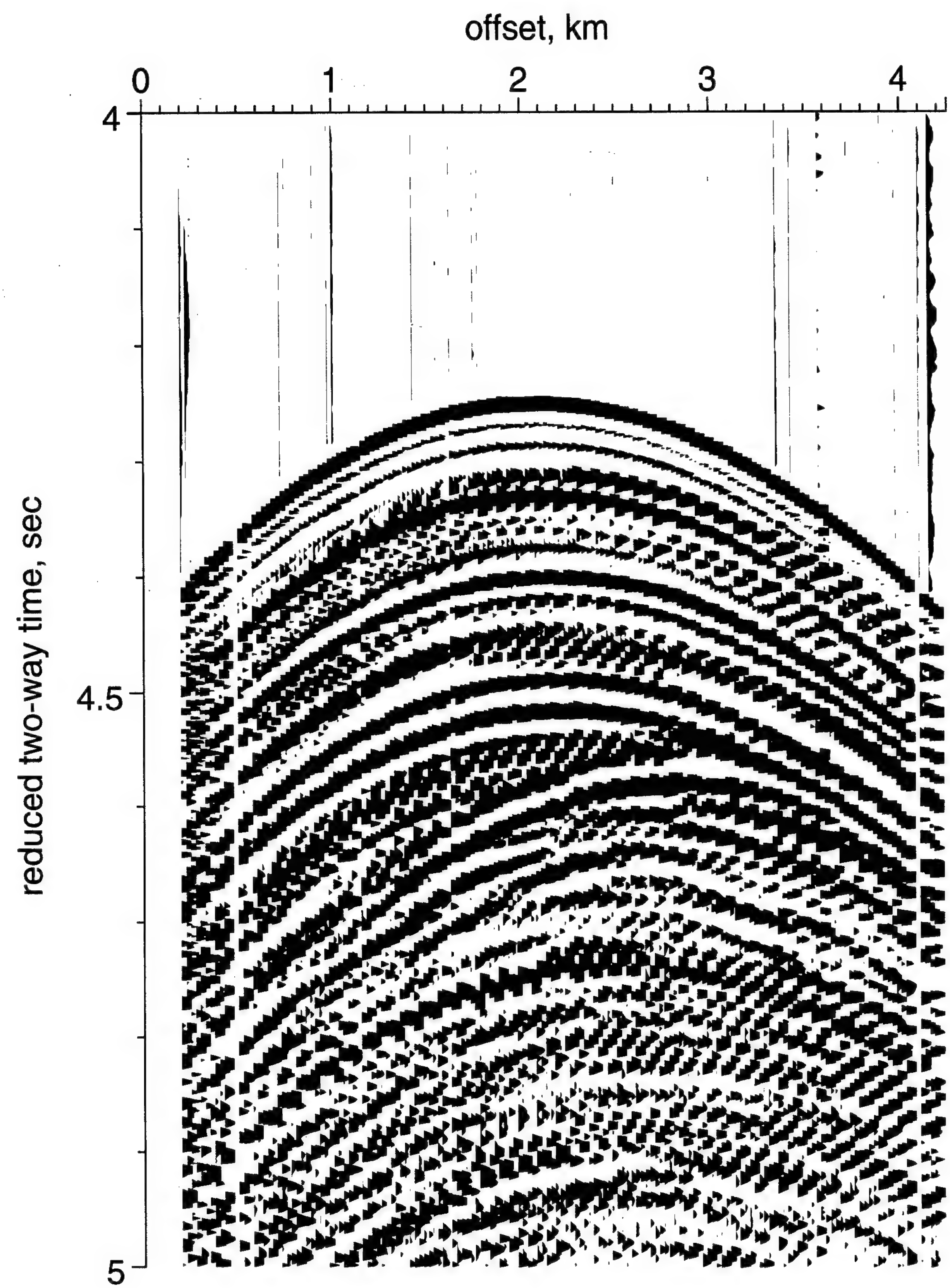
Figure 3



Crustal age 5.2my. Layer 2A is very thin

L-DEO mcs line 1266 cdp 60825

Figure 4



Layer 2A, as defined by its top and bottom reflectors,is fast and thick

L-DEO MCS line 1266 cdp 34745 crustal age -4.2 my

Figure 5

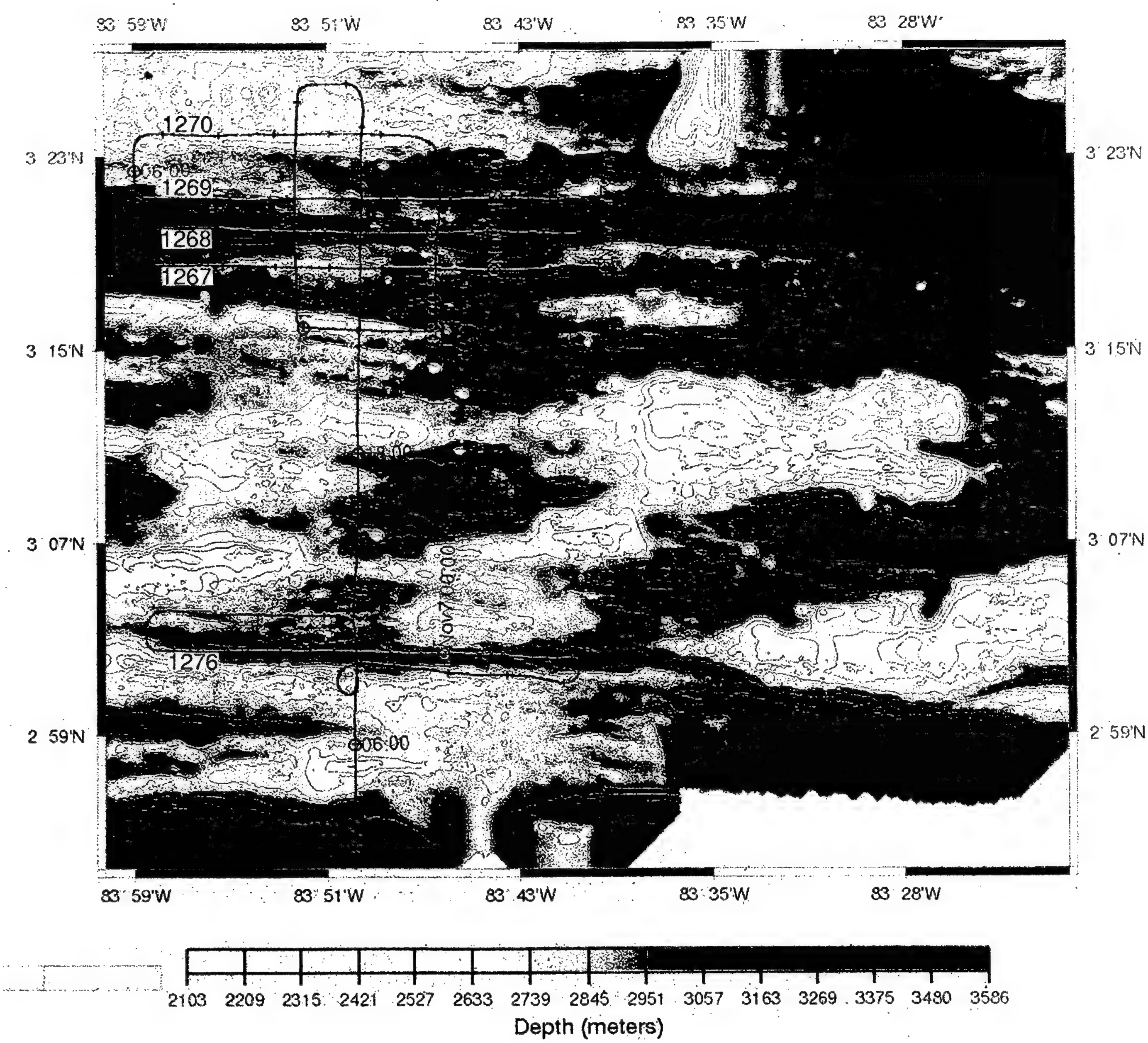

83° 59'W
83° 51'W
83° 43'W
83° 35'W
83° 28'W
3° 23'N
3° 15'N
3° 07'N
2° 59'N
1270
1269
1268
1267
1276
06:00
06:00
2103
2209
2315
2421
2527
2633
2739
2845
2951
3057
3163
3269
3375
3480
3586
Depth (meters)

Figure 6.

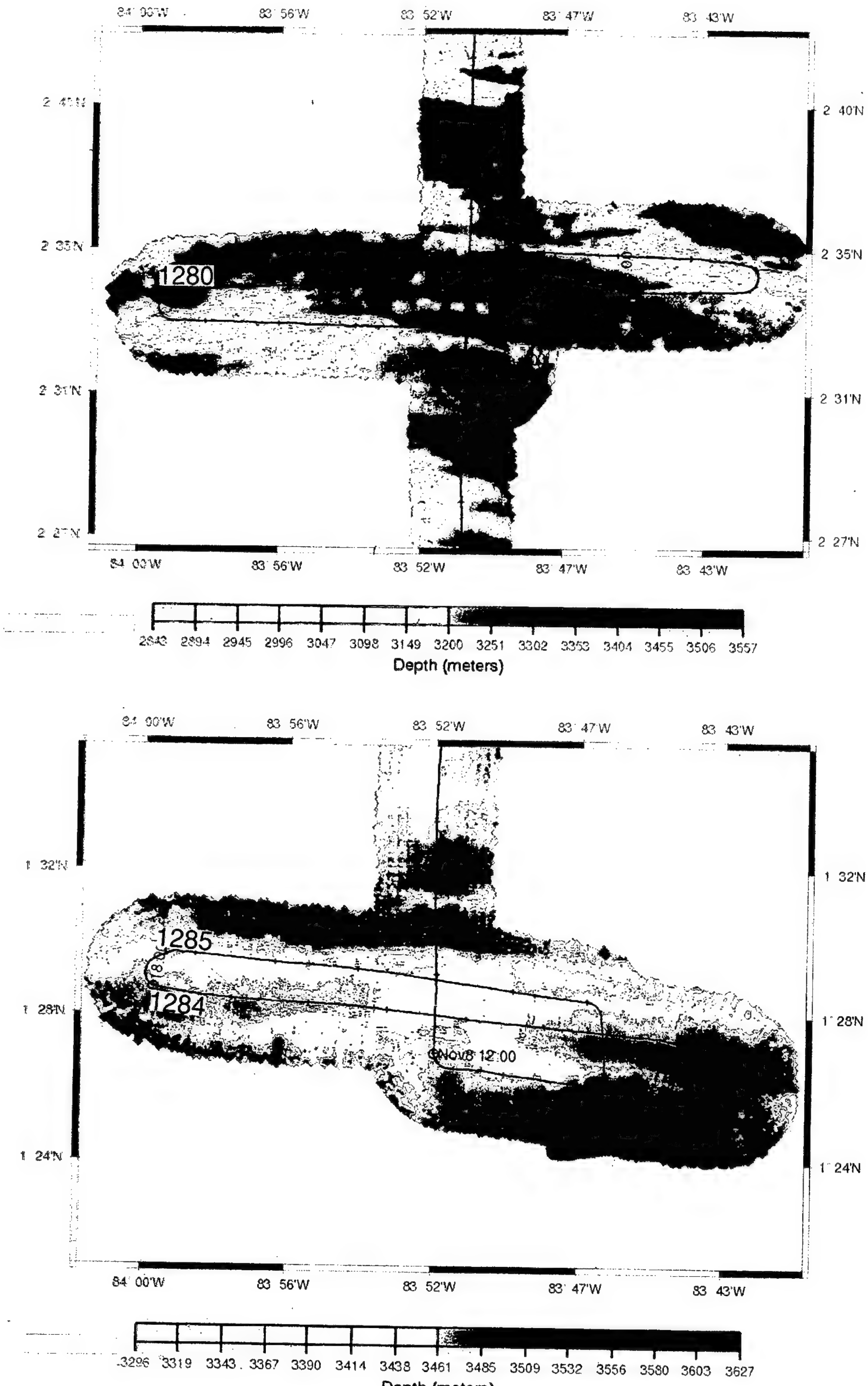

84° 00'W
83° 56'W
83° 52'W
83° 47'W
83° 43'W
2° 40'N
2° 35'N
2° 31'N
2° 27'N
1280
2843 2894 2945 2996 3047 3098 3149 3200 3251 3302 3353 3404 3455 3506 3557
Depth (meters)
84° 00'W
83° 56'W
83° 52'W
83° 47'W
83° 43'W
1° 32'N
1° 28'N
1° 24'N
1285
1284
Nov 8 12:00
3296 3319 3343 3367 3390 3414 3438 3461 3485 3509 3532 3556 3580 3603 3627
Depth (meters)

Figure 7.

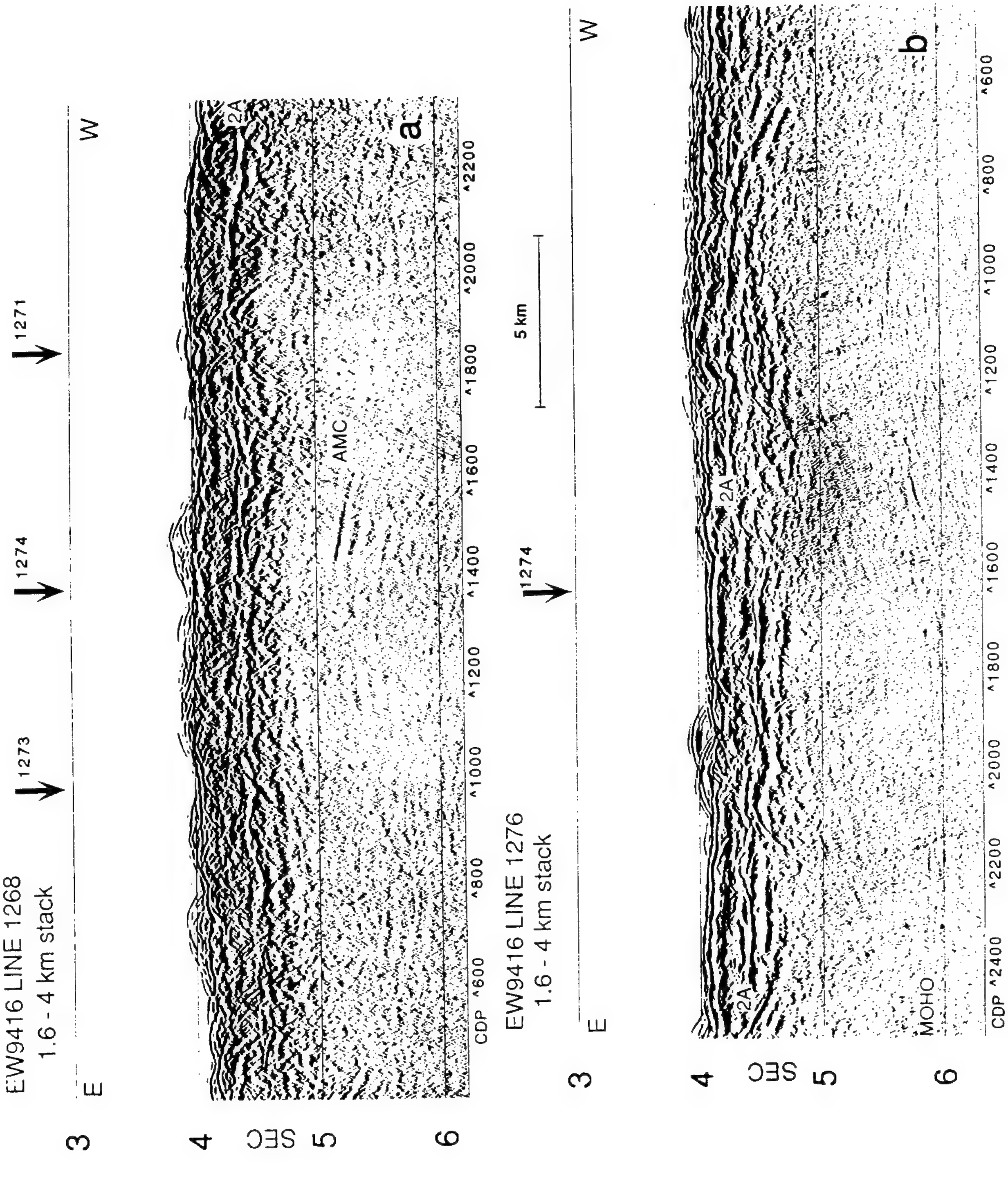

EW9416 LINE 1268
1.6 - 4 km stack
E
W
1273
1274
1271
2A
AMC
a
CDP ^600
^800
^1000
^1200
^1400
^1600
^1800
^2000
^2200
3
4
5
6
SEC
5 km
EW9416 LINE 1276
1.6 - 4 km stack
E
W
1274
2A
MOHO
b
CDP ^2400
^2200
^2000
^1800
^1600
^1400
^1200
^1000
^800
^600

Figure 8.

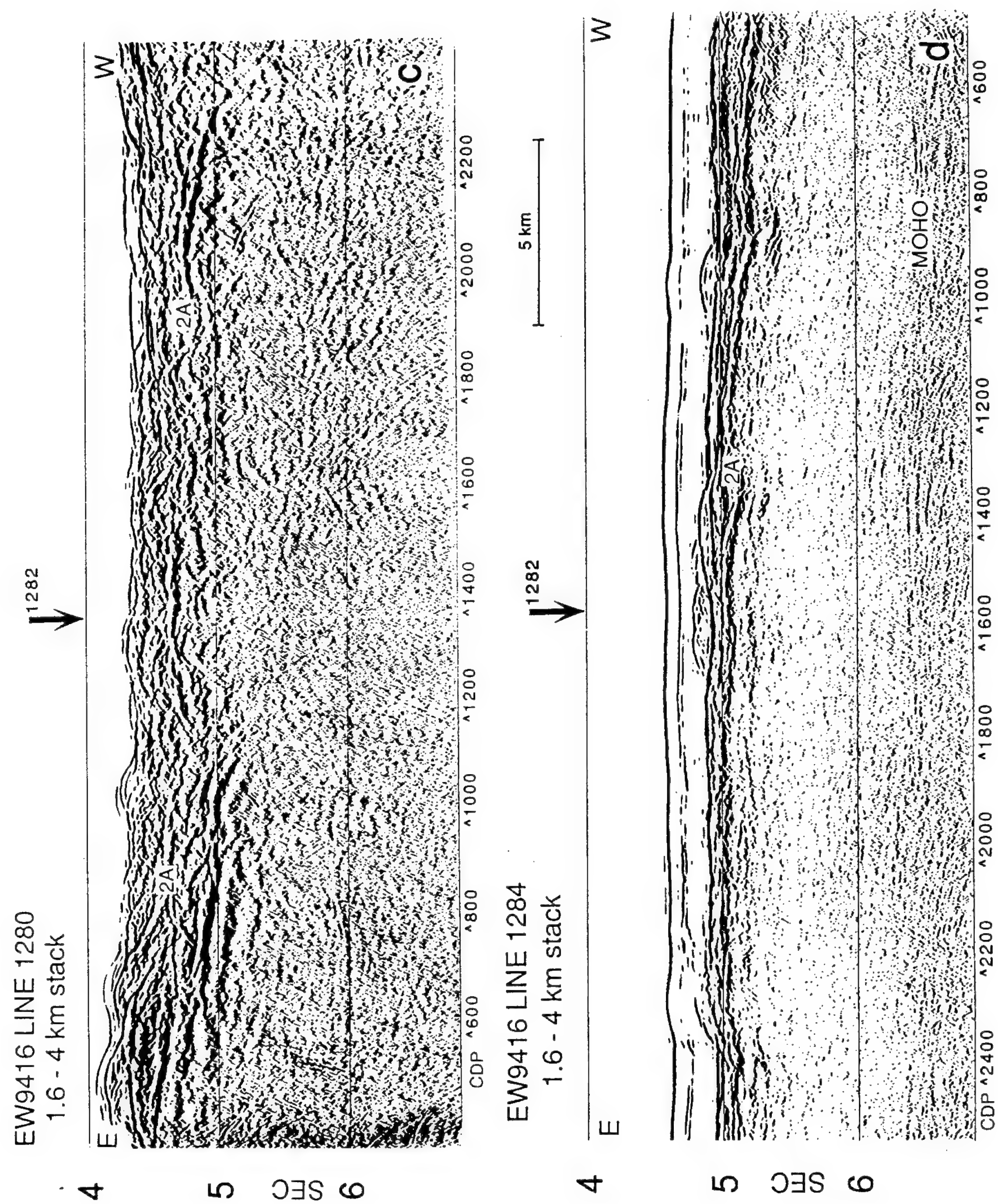


Figure 8, cont.

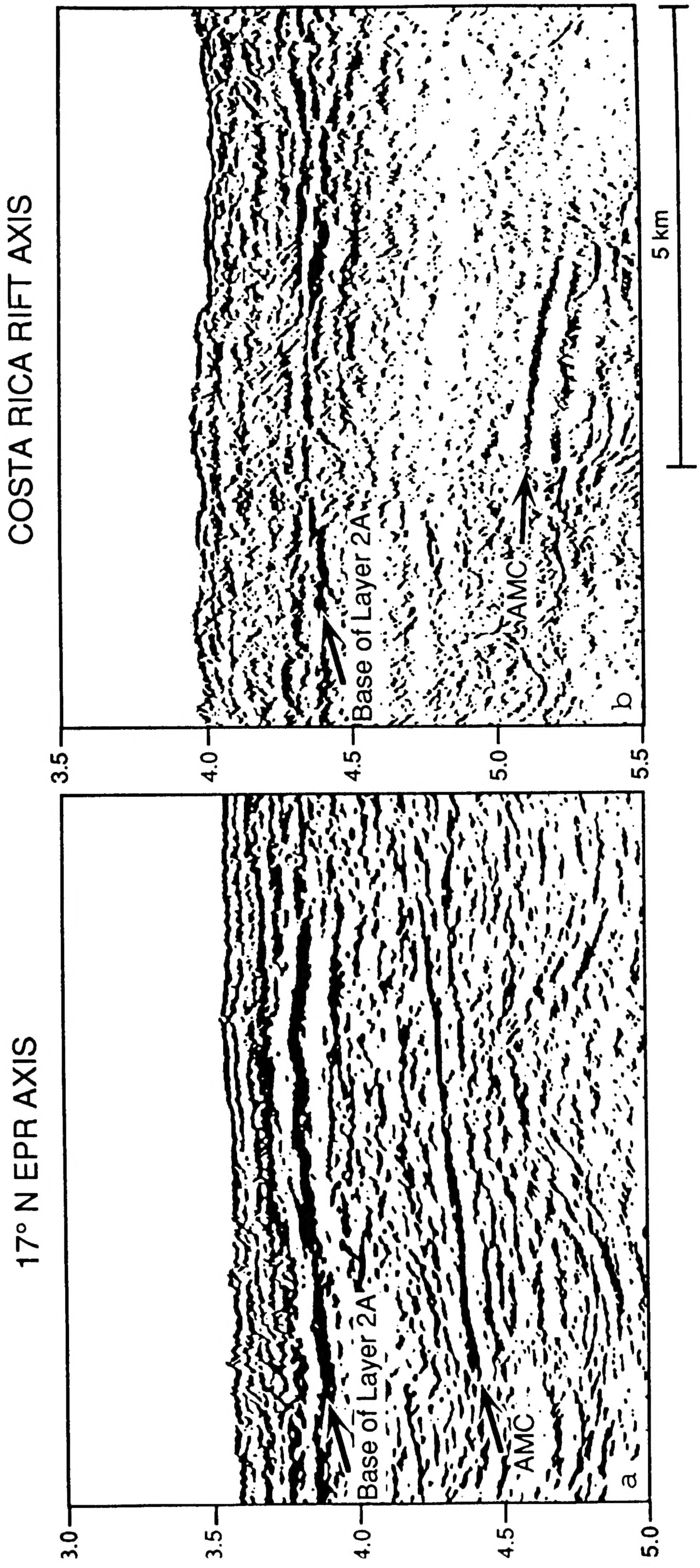
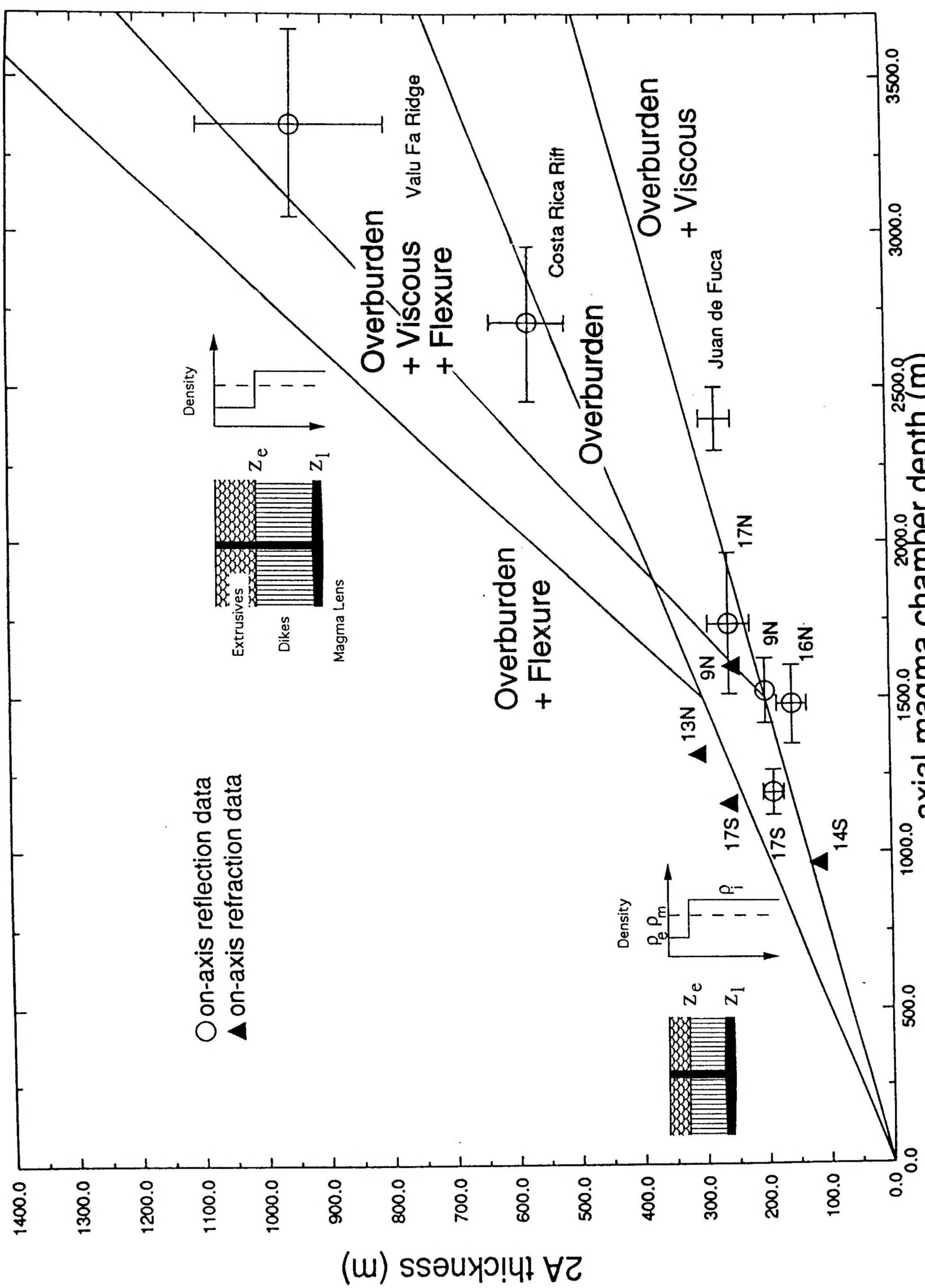

17° N EPR AXIS
COSTA RICA RIFT AXIS
3.0
3.5
4.0
4.5
5.0
5.5
Base of Layer 2A
AMC
a
b
5 km

Figure 9.



on-axis reflection data
on-axis refraction data
Overburden + Viscous + Flexure
Overburden
Overburden + Viscous
Overburden + Flexure
Valu Fa Ridge
Costa Rica Rift
Juan de Fuca
13N
9N
17N
16N
17S
14S
Extrusives
Dikes
Magma Lens
Density
Z_e
Z_l
ρ_e ρ_m
ρ_i
axial magma chamber depth (m)
2A thickness (m)
0.0
500.0
1000.0
1500.0
2000.0
2500.0
3000.0
3500.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
1100.0
1200.0
1300.0
1400.0

Figure 10.

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Consensus reached at ONR Workshop on Investigations of Young Oceanic Crust (3/93) was that marine geophysical surveys should be conducted in one or more "corridors" in the Eastern Pacific. It was recognized that MCS reflection profiling was an important part of such surveys, despite their relatively high cost. Excellent results were gained during two such profiling efforts, which were carried out as "add-on" surveys, one attached to a NSF-funded survey and the other during a transit leg. In both cases, transit, mobilization and demobilization costs were minimal and the maximum amount of data possible was obtained - given the available funding.

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